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Edited by:
Jon D. Hanson
Marvin J. Shaffer
Dan A. Ball
C. Vern Cole

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Simulation of the Corn Rootworm/Corn System with Emphasis on Improved Pest Mangement

Steven E. Naranjo, Agricultural Research Service, Phoenix, Arizona.

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INTRODUCTION

Corn rootworms, *Diabrotica* spp., are considered important pests of corn throughout the corn-growing regions of the Great Plains. Larvae inhabit the soil and feed on the roots of corn. This feeding impacts yield by causing physiological stress to the plant and by promoting lodging. In the United States, the combined annual cost of insecticides for pest suppression and value of crop loss due to larval feeding exceeds one-billion dollars (Metcalf 1986). This estimate does not include external costs of environmental degradation and health risks associated with the application of the highly toxic, broad-spectrum pesticides used for corn rootworm suppression.

Management strategies that reduce the impact of corn rootworm damage and promote sustained corn production are possible. However, such strategies must be based on an understanding of the functioning of the entire agroecosystem. Design of sustainable agricultural systems that include corn will depend on the combined effort of researchers from many disciplines. Mathematical modelling and simulation will play a central role in this effort. Models will provide a framework for synthesizing research information, formulating working hypotheses, and evaluating crop production systems. Models of pest population dynamics will form an important part of larger models describing entire agroecosystems.

Some effort has been devoted to developing population dynamics models for insect pests of corn (e.g. Stinner et al. 1974, Mooney and Turpin 1976, Pontius et al. 1984, Onstad 1988). This paper describes a population model for *Diabrotica barberi*, the northern corn rootworm. The model is structured to allow direct connection between insect dynamics and crop development and, thus, may be easily linked with more extensive crop simulation models. First, the general life cycle and some of the unique features of the interaction between *D. barberi* and corn are described. A process-oriented population model is then briefly described and the model is then used to explore the impact of crop phenology on beetle population dynamics and to determine the potential value of manipulating crop development for reducing corn rootworm damage and pesticide usage.

SYSTEM FEATURES

Northern corn rootworms are univoltine or semivoltine and as larvae are functionally monophagous on the roots of corn. Larvae mature and adults begin to emerge from the soil in mid-summer at about the time that corn starts to flower. Emergence typically continues into early fall. Adults feed on the silks and pollen of corn, but may disperse widely to feed on the pollen of a variety of other flowering plants. Females oviposit in the soil from late July until early October throughout most of their geographic range. The eggs undergo diapause for one or more winters and hatch the following spring. Details of life history and biology are given in Chiang (1973) and Krysan (1986). Because of the life cycle of corn rootworms and the constraints of monophagy in the larval stage, these insects are most often pests in fields that have been in corn at least two seasons. Larval population size and damage potential one year is directly related to the abundance and ovipositional activity of female beetles the previous year. Consequently, the decision to suppress larval populations in a given field through the planting-time application of a soil insecticide is typically based on experience, aversion to the risk of crop damage, or, if available, on information about adult population levels gathered 9-10 months earlier.

The host plant, corn, plays a key role in the population dynamics of *D. barberi* (Hill and Mayo 1980, Branson and Krysan 1981, Naranjo and Sawyer 1988a). As a consequence, this insect demonstrates a high degree of temporal coincidence with corn. Egg diapause synchronizes larval hatch and development with corn roots between seasons, and the timing of various population processes synchronizes the adult with the flowering stage of corn within a season (Naranjo and Sawyer 1988a). This within-season synchrony of adult beetles with corn flowers is a striking feature of this system as it allows efficient exploitation of the brief occurrence of a high-quality food resource. Synchrony is maintained despite temporal shifts in crop phenology that may occur through changes in planting dates and cultivar selection.

However, seasonal population structure is dramatically affected by shifts in the timing of flowering (Fig. 1). In Figure 1 the horizontal bars represent the period of time during which more than 5% of the corn was in flower; hatched areas within bars the period of pollen shed. Curve bounding the open area represents total beetle density; open areas represent male component, stippled areas represent immature females component and dark areas represent mature females. Field labels indicate the cultivar used and the relative time of planting. As flowering is progressively delayed in a field, beetle population becomes increasingly dominated by mature, egg-laying females. As a result, total oviposition by a given population of beetles increases in fields that flower later in the season. The importance of crop phenology on the dynamics of this pest may offer avenues for insect population management based on the cultural manipulation of crop phenology rather than pest control based primarily on use of soil insecticides.

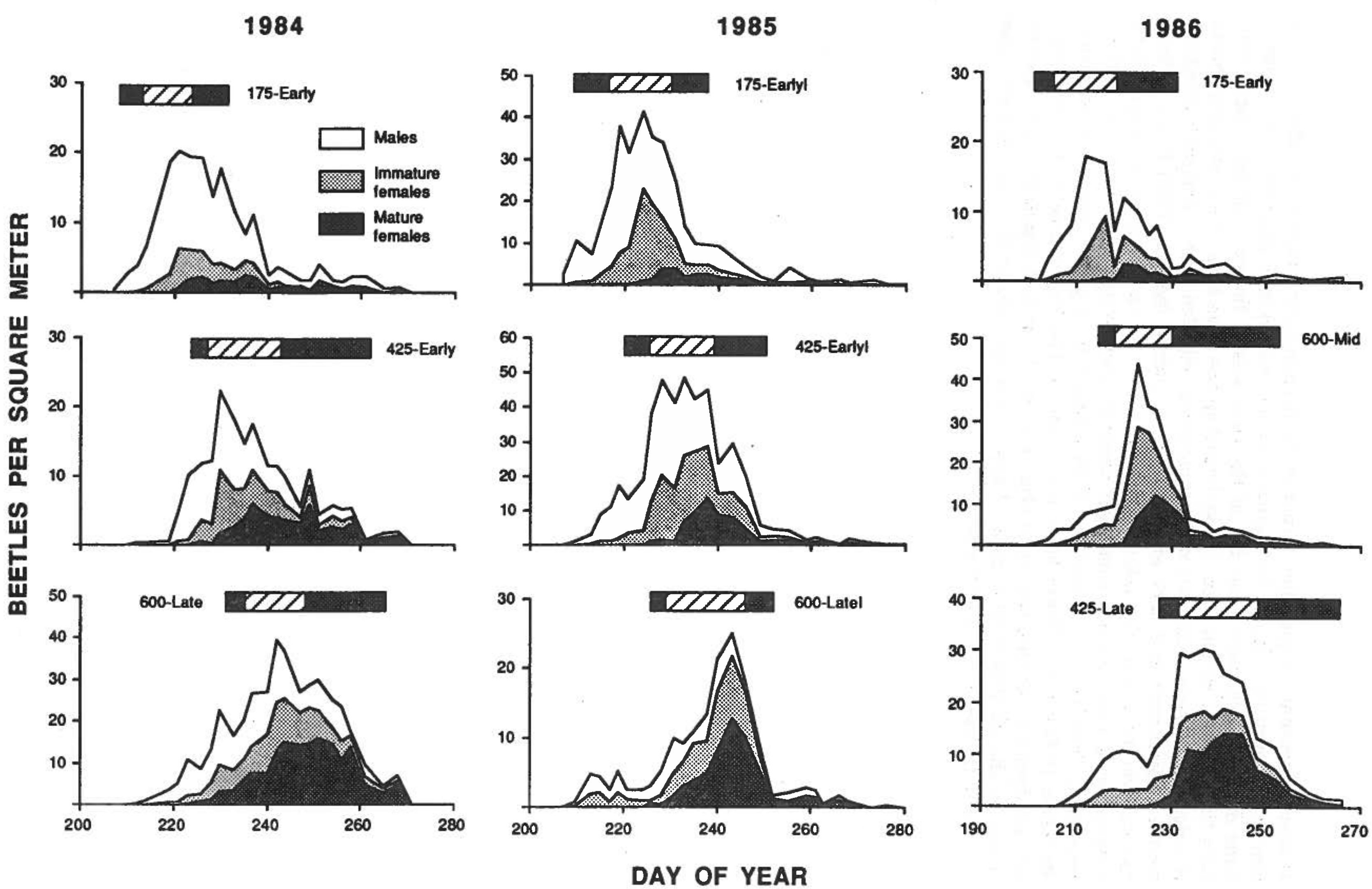

Figure 1. Observed beetle population density and composition in cornfields flowering at different times through the season. See text for a description. (Reproduced with permission of Environmental Entomology).

The model presented in the following section describes the influence of crop phenology on the population dynamics of *D. barberi* by explicitly modelling the relationships between corn phenology and the processes governing insect abundance in a specific field. The key issue here is to understand the factors determining the deposition of eggs in a specific field, and thus, the damage potential from larval feeding if corn is planted in the same site the following season. Therefore, the model focuses on adult beetles and does not explicitly describe the development, survival, and feeding of the immature stages (eggs and larvae).

SYSTEM MODEL

Relevant population processes for adult beetles can be summarized as emergence, mortality, dispersal, reproductive development, and oviposition. The system model incorporates submodels for each of these processes, many of which are directly influenced by corn phenology (Fig. 2). The basis of the model is a cohort-structured phenology model which incorporates variation in developmental rates between individuals and allows the maintenance of an age-structure in the female population (Naranjo and Sawyer 1988b). Adult recruitment is achieved by simulating the emergence of each sex over the season as a function of temperature, planting date, and cultivar. This submodel accounts for development of all immature stages including eggs which are assumed to begin accumulating developmental time when soil temperatures (5 cm) exceed 10°C anytime after 1 March (termination of diapause). Upon emergence, females pass through three developmental stages: prereproductive, reproductive and postreproductive, with the time spent in each stage being a distributed variable that is dependent on temperature. While in the reproductive stage, females oviposit at an age-specific rate that is temperature-dependent. Mortality and net dispersal (emigration-immigration) account for population attrition and both are functions of crop phenology which is explicitly modelled as a stochastic temperature-dependent process. Rates of mortality and net dispersal are lowest at the time of peak flower (period in time when the greatest proportion of corn plants are flowering) and greatest when no flowers are present.

The model predicts cumulative emergence, daily densities of adult beetles, age-structure, oviposition and plant development, and is initiated by specifying weather data, the cultivar and planting date of the field on physiological scales, and the total number of beetles that will emerge over the growing season. A complete and detailed description of model equations, parameter estimation and model operation can be found in Naranjo and Sawyer (1989).

To date various component submodels and the overall system model have been compared to independent data collected from two sites over a 2-year period, comprising eight fields (Naranjo and Sawyer 1989). Based on these comparisons, the model appears to incorporate the essential features of this insect/plant system and faithfully describes the dynamic behavior of the real system. The model has not been tested over a wide geographic range.

SYSTEM ANALYSIS

In developing cropping practices that reduce the number of external inputs and promote system sustainability, cultural factors such as planting date, cultivar selection, tillage and crop rotation schemes play an important role. Given the close

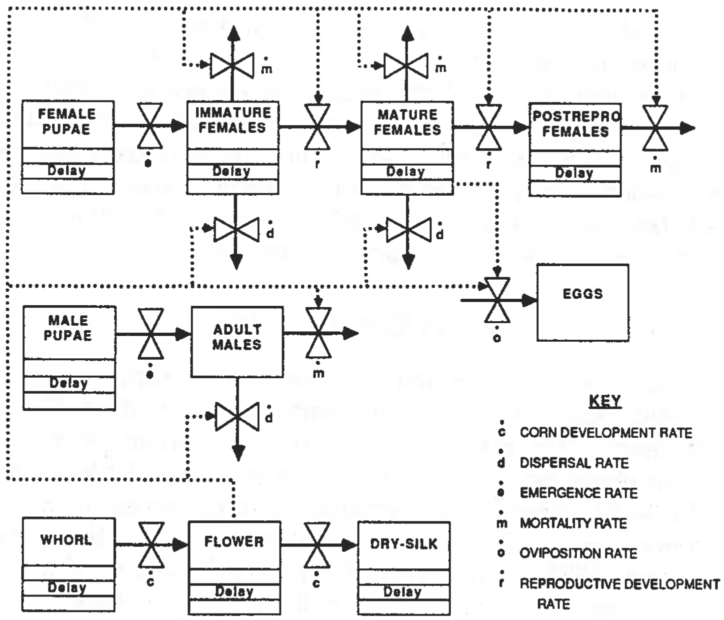

Figure 2. Relational flow diagram of the corn rootworm/corn system model. (Reproduced with permission from the Canadian Entomologist).

association between *D. barberi* and its host plant, any factor that influences the temporal or spatial features of the crop will have a direct effect on pest population dynamics. Rotation of corn with non-host crops, particularly rotations where corn is present only every 3-4 years, would clearly be an effective means of eliminating or reducing the corn rootworm problem. Tillage may also influence pest population dynamics by altering the subterranean environment of the larval stage (see Gustin et al. this proceedings). The manipulation of crop phenology, through alteration of planting date and cultivar selection, to reduce egg deposition and, thus, subsequent damage in a given field, may also represent a feasible management tool worthy of consideration. Results presented here demonstrate the impact of corn phenology on the population dynamics of *D. barberi*.

Figure 3 presents the results of analyses to examine the sensitivity of system behavior to changes in model parameters describing corn phenology. The standard simulation against which these changes were evaluated utilized a typical early-planted, mid-season cultivar and a 30-year average temperature data set. Total oviposition and the mean daily rate of oviposition per adult beetle over the season were used to gauge changes in system behavior. In most instances a 10% change in the value of a model parameter altered model output by over 10%. By far, the parameters with the greatest impact were those defining the developmental transition from flowering to post-flowering plants and those defining the overall period of flower availability (Fig. 3). Changes in the parameter defining the transition from pre-flowering to flowering plants had relatively little influence on system behavior. This suggests that factors which alter crop phenology later in the season are more critical. These analyses demonstrate that despite the close synchrony between adult beetles and flowering corn, temporal shifts in crop phenology have a significant and predictable impact on population structure and resultant oviposition.

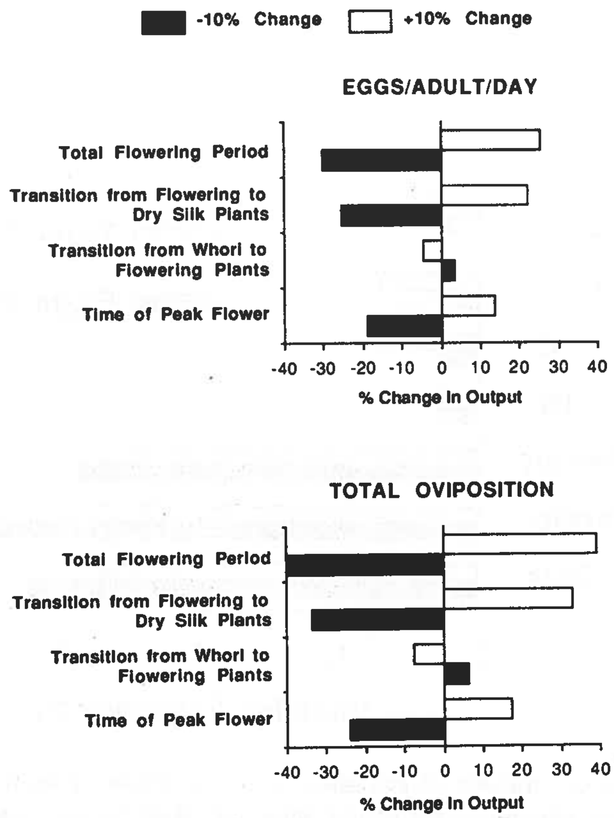

Figure 3. Sensitivity of model behavior to changes in model parameters describing corn plant phenology. Sensitivity is reported as the percentage change in model output for the indicated percentage change in model parameters.

Other analyses were performed to evaluate the interactions of various factors that might be used to alter crop phenology. A factorial sensitivity analysis was conducted with three levels of each of three factors: planting date, cultivar, and the overall period of flowering. Results demonstrated that interaction terms explained relatively little (<10% in any case) of the variation in system output (Fig. 4). Furthermore, there was little difference in the amount of variation explained by the three main factors. This suggests that it makes little difference which single cultural factor is manipulated. Planting early, using a short season (early flowering) cultivar, or a cultivar with a short flowering period will all decrease egg deposition in a field by roughly equivalent amounts.

Selection of the best practical combination of cultural factors to manipulate is problematic. Theoretically, the best strategy for minimizing oviposition in a specific field is to plant an early-season, short-flowering cultivar early in the season. However, the particular strategy employed will, in reality, depend on geographical, agronomic, and economic considerations beyond the scope of this analysis. For instance, the selection of a cultivar may be more influenced by the desire for certain agronomic characteristics, such as drought tolerance, that have little to do with timing and duration of flowering. Likewise, it may not be feasible to plant full-season hybrids or delay planting in areas with short growing seasons. Contrarily, it may not be desirable to plant a short-season cultivar that fails to use the full growing season. Compounding the problem is the impact of environmental variation, particularly seasonal temperature patterns (see below), which influence both insect and plant processes.

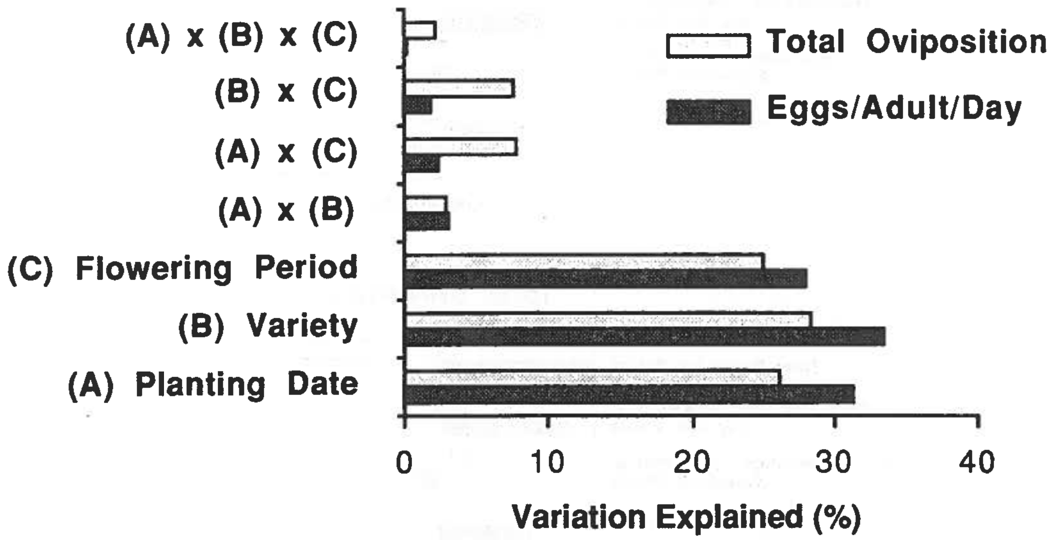

Figure 4. Simultaneous analysis of the effect of three levels of each of three factors influencing crop phenology on model behavior. Results are reported as the percentage of variation in model output explained by changes in each factor or factor interaction.

A final analysis was conducted to determine the impact of environmental variation (temperature) on beetle dynamics and to highlight the importance of observations of crop phenology in the decision-making process for pest suppression. Simulation was used to generate the response surfaces that depict the relationship between adult abundance and oviposition as a function of planting date, cultivar and seasonal temperature pattern (Fig. 5). These surfaces provide clear evidence of the dynamic nature of the relationship between adult abundance and oviposition.

As noted earlier, if the information is available, the decision to apply soil insecticides in continuous corn is usually made on the basis of adult population densities the previous season. Unfortunately, the relationship between adult abundance and damage potential is poorly understood (Foster et al. 1986). The response surfaces in Figure 5 indicate at least one component that is not presently involved in this decision process, the dynamic nature of egg deposition in response to changing crop phenology and temperature. If this information were considered, it might improve the efficiency of the decision process by eliminating the application of insecticides in cases where they are unnecessary. For example, because there is less oviposition per beetle in earlier-planted, earlier-flowering fields, a higher density of adult beetles would be needed to trigger the action for insect suppression. The opposite would be true for later-planted, later-flowering fields.

CONCLUSIONS

The development of cropping systems which require fewer external inputs and utilize the inherent properties of the crops and environment will require the combined effort of researchers from many disciplines. Pest control and management will form

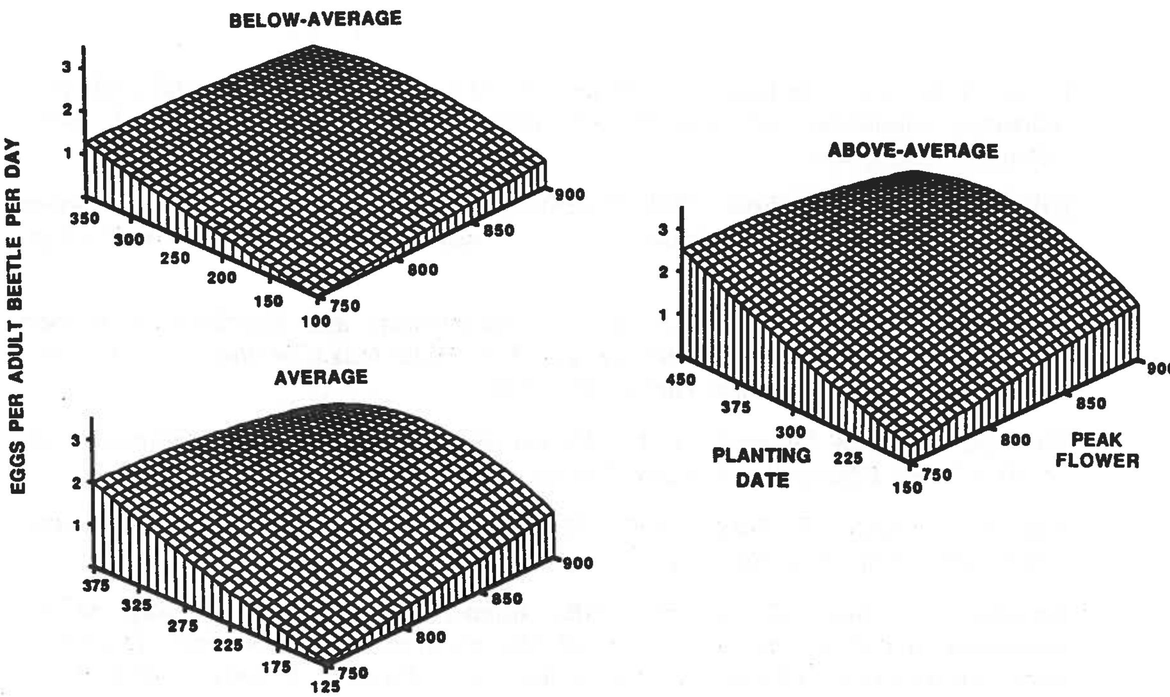

Figure 5. Simulation generated response surfaces depicting the relationship between adult abundance and oviposition (eggs/adult beetle/day) as a function of planting date, cultivar, and temperature. (Reproduced with permission from the Canadian Entomologist).

a integral part of the effort. As large-scale agroecosystem models are developed. it will be essential to include pest population dynamics models to more fully understand these systems and devise practical cropping systems. The model described and analyzed here could be easily incorporated into existing or evolving crop simulation models due to its explicit recognition of the insect/host plant interface.

Results of model analyses emphasize the critical importance of crop phenology to the population dynamics of *D. barberi* and its potential importance in the management of this serious pest. Manipulation of planting dates and cultivar selection, either individually or in combination, represent a powerful set of means for reducing site-specific oviposition. Along with agronomic and economic considerations, these cultural manipulations and an understanding of their impact on pest population dynamics could represent important tactics towards developing more sustainable cropping systems which de-emphasize the input of insecticides for pest suppression.

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